2021

Chapter Three :

Junction- Diode Characteristics

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3.1 P-N Junction in Equilibrium (Zero Bias)

In a p – n junction, without an external applied voltage, an equilibrium condition is reached in which a potential difference forms across the junction. This potential difference is called built in potential V_D .

Consider the special case indicated in Fig. 3.1. The left half of the bar is *p-type* with a constant concentration N_A , whereas the right half is *n-type* with a uniform density N_D. The dashed plane is a metallurgical (p-n) junction separating the two sections with different concentration. This type of doping, where the density changes abruptly from *p-* to *n-type* , is called step grading. The step-graded junction is located at the plane where the concentration is zero.

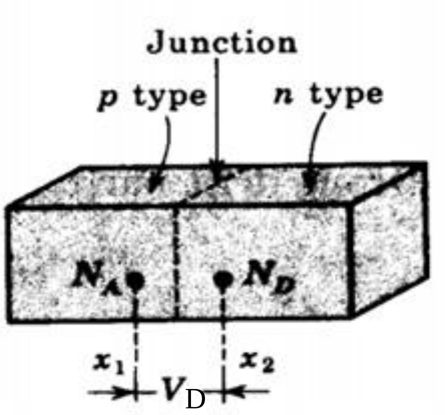

Fig. 3.1 Zero Bias (p – n) Junction.

$$V_D = V_{21} = V_T \ln \frac{p_p}{p_n}$$

$$where \quad p_p = N_A \quad and \quad p_n = \frac{{n_i}^2}{N_D}$$

$$V_D = V_T \ln\frac{N_A N_D}{{n_i}^2}$$

V_T = KT/e = T/11600

If donor impurites are introduced into one side and acceptors into the other side of a single crystal of a semiconductor, a *p-n* junction is formed, as in Fig. 3.1. Such a system is illustrated in more schematic detail in Fig. 3.2 . The donor ion is represented by a plus sign because, after this impurity atom "donates" an electron, it becomes a positive ion. The acceptor ion is indicated by a minus sign because, after this atom "accepts" an electron, it becomes a negative ion. Initially, there are nominally only *p-type* carriers to the left of the junction and only *n-type* carriers to the right.

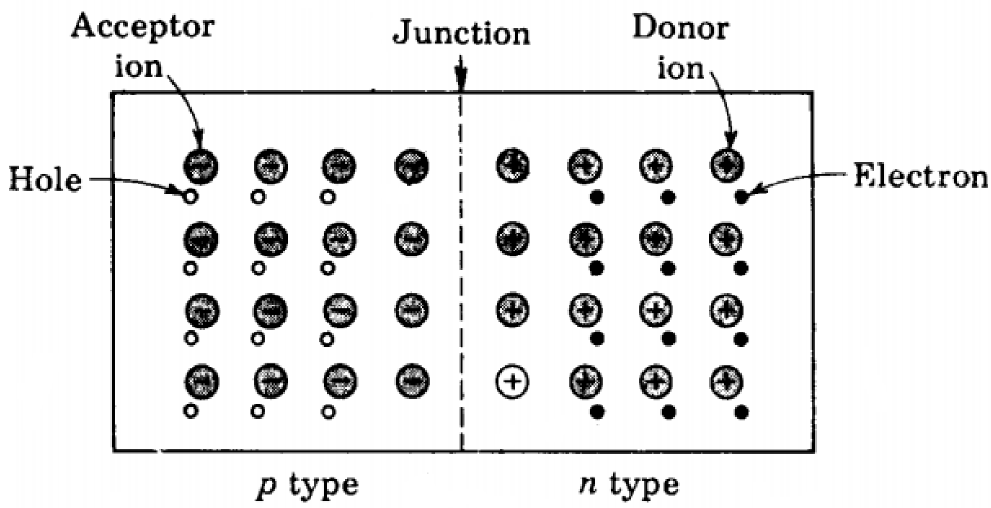

Fig. 3.2 A schematic diagram of P-N junction.

The region of the junction is depleted of mobile charges, it is called the *depletion region*, the *space charge region*, or the *transition region*.

The thickness of this region is of the order of the wavelength of visible light (0.5 micron = 0.5μm). Within this very narrow space charge layer there are no mobile carriers. To the left of this region the carrier concentration is $p=N_A$ and to its right it is n= N_D.

The space charge density is zero at the junction. It is positive to the right and negative to the left of the junction.

The two terminal device (called a junction diode) , as shown in Fig. 3.3, is a device that conducts current in only one direction.

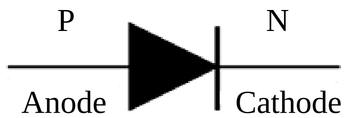

Fig. 3.3 Diode schematic symbol.

3.2 P-N Junction Bias

If the external potential of **V volt** is applied across the P-N junction this will bias the diode. There are two type of diode bias :

3.2.1 Forward Bias

Forward Bias An external voltage applied with the polarity shown in Fig. 3.4. Where Connecting the positive terminal of the external voltage source to the p-side and the negative terminal to the n-side will cause a forward bias for the junction

The application of **Forward Bias** potential **V** will cause an injection of electrons from n-side and hole from p-side in opposite direction across the junction region and some of these carriers will recombine with the ions near the boundary region and reduce the width of depletion region.

On being injected across the junction, these carriers immediately become minority carriers.

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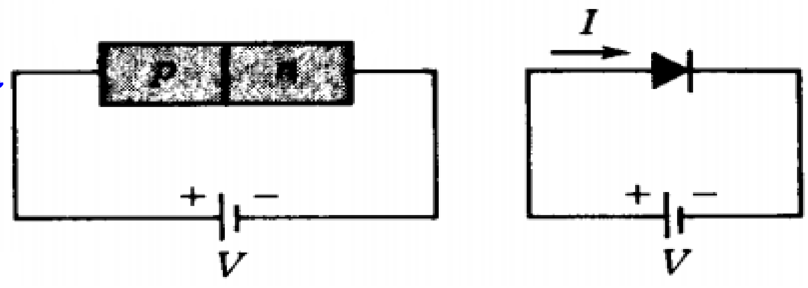

Fig 3.4 P-N Junction biased in the forward direction.

3.2.2 Reverse Bias

Reverse Bias If the positive terminal of the applied voltage connect to the n-type and the negative terminal to p-type, as shown in Fig. 3.5 , the junction will bias in reverse direction. The depletion region has been winded, that result to overcome the region from the majority carrier more and more carriers.

The current in reverse-bias condition called **Reverse Saturation Current (I_S).**

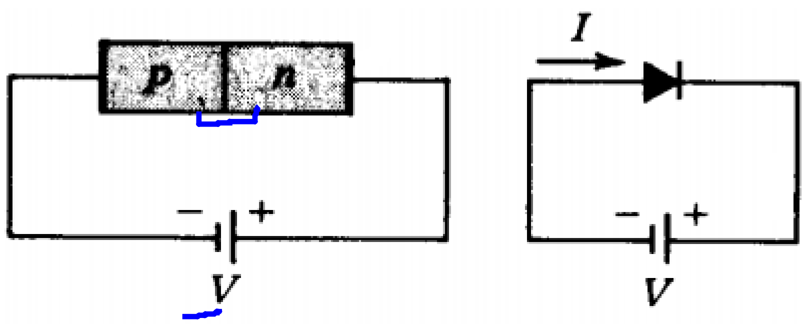

Fig 3.5 P-N Junction biased in the reverse direction.

Example 1:

A PN junction was formed from two pieces of silicon contain $N_D = 10^{24} m^{-3}$ and $N_A = 10^{20} m^{-3}$ at 300°K. Calculate the built in potential of the p-n junction where $n_i = 1.45 \times 10^{16} m^{-3}$.

Sol:

$$V_D = \frac{kT}{e} \ln \frac{N_D N_A}{n_i^2}$$

$$= \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}} \ln \frac{10^{24} \times 10^{20}}{(1.45 \times 10^{16})^2} = 0.7 \text{ volt}$$

Example 2:

The conductivity of n-side in the Ge PN junction is 10^4 s/m and for the p-side is 10^2 s/m . Find the built in potential for the junction at 300°K? where $n_i = 2.5 \times 10^{19} m^{-3}$, $\mu_n = 0.36 \, m^2/v.s$ and $\mu_p = 0.16 \, m^2/v.s$.

sol:

At n-side:

$$\sigma_{(n)} = n_n e \mu_n + p_n e \mu_p = N_D e \mu_n + \frac{n_i^2}{N_D} e \mu_p$$

$$10^4 = 1.6 \times 10^{-19} \left(0.36 \, N_D + \frac{(2.5 \times 10^{19})^2}{N_D} \times 0.16 \right)$$

$$N_D = 1.7 \times 10^{23} m^{-3}$$

At p-side:

$$\sigma_{(p)} = p_p e \mu_p + n_p e \mu_n = N_A e \mu_p + \frac{n_i^2}{N_A} e \mu_n$$

$$10^2 = 1.6 \times 10^{-19} \left(0.16 \, N_A + \frac{(2.5 \times 10^{19})^2}{N_A} \times 0.36 \right)$$

$$N_A = 3.9 \times 10^{21} m^{-3}$$

$$V_D = \frac{kT}{e} \ln \frac{N_D N_A}{n_i^2}$$

$$= \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}} \ln \frac{1.7 \times 10^{23} \times 3.9 \times 10^{21}}{(2.5 \times 10^{19})^2}$$

$$= 0.36 \text{volt}$$

3.3 The Volt - Ampere Characteristics of Diode

The relationship between the current that passed through the diode and the voltage applied at its ends is exponential relationship, where the expression for the diode current **I** is :

$$I = I_s \left(e^{\frac{V}{\eta V_T}} - 1 \right) \qquad \text{.......(3.1)}$$

$$I = I_s \, e^{\frac{V}{\eta V_T}} - I_s$$

Where : V : the applied voltage.

V_T : the volt equivalent of temperature and is given by :

V_T = T / 11600 = KT/e .

At room temperature (T = 300° K) , V_T = 0.026 V = 26 mV.

I_s : Reverse saturation current.

η : constant , for Ge = 1 , Si = 2 .

The form of Volt -Ampere characteristic described by eqn. (3.1) is shown in Fig. 3.6 .

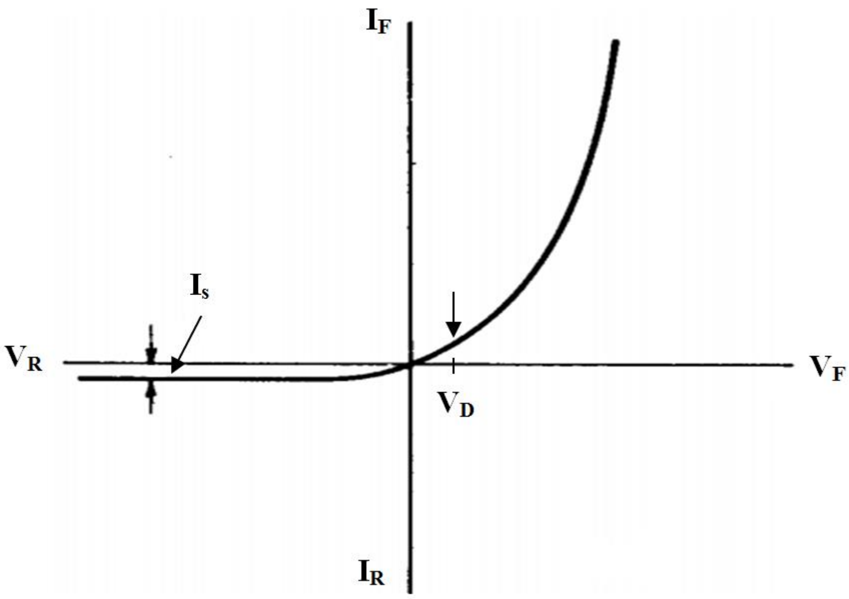

Fig. 3.6 The Volt - Ampere characteristic of an ideal diode .

When the diode is **Reverse Biased** and V is several times V_T , then $\mathbf{I \approx I_s}$ as shown in the left side of Fig. 3.6 . The reverse current is therefore constant , independent of the applied reverse bias.

In **Forward Bias**, the current beyond the $\mathbf{V_D}$ **(Cut in or Threshold voltage)** is rises very rapidly, as shown in the right side of Fig. 3.6.
$\mathbf{V_D}$ is approximately 0.3 V for Ge and 0.7 for Si.

In forward bias, eqn. (3.1) can be written as :

$$I_F = I_s \ e^{\frac{V}{\eta V_T}} \qquad \ldots \ldots \ldots (3.2)$$

3.5 Diffusion Capacitance (C_D)

Diffusion capacitance occurs in a forward biased p – n junction diode. The diffusion capacitance occurs due to stored charge of minority electrons and minority holes near the depletion region.

When forward bias voltage is applied to the p – n junction diode, electrons (majority carriers) in the n-region will move into the p-region and recombines with the holes. In the similar way, holes in the p-region will move into the n-region and recombines with electrons. As a result, the width of depletion region decreases.

The electrons (majority carriers) which cross the depletion region and enter into the p-region will become minority carriers of the p-region similarly; the holes (majority carriers) which cross the depletion region and enter into the n-region will become minority carriers of the n-region.

A large number of charge carriers, which try to move into another region will be accumulated near the depletion region before the recombine with majority carriers. As a result, a large amount of charge is stored at both sides of the depletion region as shown in Fig. 3.8.

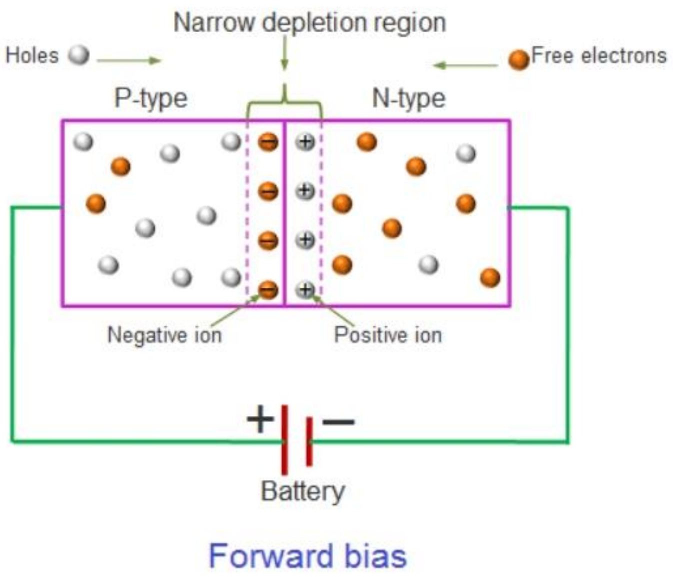

Fig. 3.8 Diffusion capacitance of p - n junction diode.

The accumulation of holes in the n-region and electrons in the p-region is separated by a very thin depletion region. This depletion region acts like insulator of the capacitor and charge stored at both sides of the depletion region acts like conducting plates of the capacitor.

The formula for diffusion capacitance is given by:

$$C_D = \frac{dQ}{dV} \quad \text{......(3.3)}$$

Where :

dQ : the change in number of minority carriers storied outside the depletion region.

dV : the change in voltage applied across diode.

If $\boldsymbol{\tau}$ is mean life time of charge carriers, and is given by: تاو

$$\tau = \frac{L^2}{D}$$

Where L is the diffusion length, and D is the diffusion constant.

Then a flow charge Q yields a diode current I is given as :

$$I = \frac{Q}{\tau} \quad \text{......(3.4)}$$

In case of forward bias current is given by :

$$I_F = I_S \; e^{\frac{V}{\eta V_T}}$$

Substitute eqn.(3.2) in eqn. (3.4) :

$$Q = \tau I_S \; e^{\frac{V}{\eta V_T}} \quad \text{........ (3.5)}$$

So, diffusion capacitance C_D in eqn.(3.3) will become :

$$C_D = \frac{dQ}{dV} = \frac{d(\tau I_S \; e^{\frac{V}{\eta V_T}} \;)}{dV}$$

$$= \frac{\tau \; I_S \; e^{\frac{V}{\eta V_T}}}{\eta V_T}$$

$$\therefore C_D = \frac{\tau \; I_F}{\eta V_T} \quad \text{.......(3.6)}$$

Example 3:

A silicon PN junction has a hole density in p-side 10^{24}m^{-3} and electron density in n-side 10^{22}m^{-3}, the cross-section area for the pn junction is 10^{-6}m^2, the mobility of the holes is $0.2\,\text{m}^2/\text{v.s}$ and the mobility of the electrons is $0.4\,\text{m}^2/\text{v.s}$. The diffusion length of the minorities are ($L_n = 300\mu\text{m}$ and $L_p = 200\mu\text{m}$). If the reverse saturation current equal to 0.04μ A and $n_i = 10^{19}\text{m}^{-3}$ at 17^{o} C. Determine:

1) The density of majority and minority carriers and the conductivity?
2) The barrier potential?
3) The diffusion constant for the both types of the carriers?
4) The junction current when $V_F = 0.25\text{v}$?
5) The junction current for the reverse bias, at high reverse voltage?
6) The diffusion capacitance of the junction?

Sol:

1)

<u>***At*** p – side</u>

$$n_p = \frac{n_i^2}{p_p} = \frac{(10^{19})^2}{10^{24}} = 10^{14}\text{m}^{-3} \text{ electrons minority}$$

$N_A = 10^{24}\text{m}^{-3}$ holes majority

$\sigma_p = e\, p_p\, \mu_p = 1.6 \times 10^{-19} \times 10^{24} \times 0.2 = 3.2 \times 10^4\ \text{s/m}$

$\sigma_n = e\, n_p\, \mu_n = 1.6 * 10^{-19} * 10^{14} * 0.4$

$\sigma_{(p)} = \sigma_p + \sigma_n$

At n − side

$$p_n = \frac{n_i^2}{n_n} = \frac{(10^{19})^2}{10^{22}} = 10^{16}\mathrm{m}^{-3}\text{holes minority}$$

$N_D = 10^{22}\mathrm{m}^{-3}$ electrons majority

$$\sigma_n = en_n\mu_n = 1.6 \times 10^{-19} \times 10^{22} \times 0.4 = 640\,\mathrm{s/m}$$

$$\sigma_p = ep_n\mu_p$$

$$\sigma_{(n)} = \sigma_p + \sigma_n$$

2) $V_D = \frac{kT}{e}\ln\frac{N_D N_A}{n_i^2} = \frac{1}{40}\ln\frac{10^{22}\times 10^{24}}{(10^{19})^2} = 0.46\text{ volt.}$

3) $D_n = \frac{kT}{e}\mu_n = \frac{1}{40} \times 0.4 = 0.01\,\mathrm{m^2/s}$

$$D_p = \frac{kT}{e}\mu_p = \frac{1}{40} \times 0.2 = 0.005\,\mathrm{m^2/s}$$

4) $I = I_S\left[\exp\left(\frac{V}{\eta\, v_T}\right) - 1\right]$

$$V_T = \frac{T}{11600} = \frac{17+273}{11600} = 0.025$$

$$I = 0.04 \times 10^{-6}\left[\exp\left(\frac{0.25}{2 * 0.025}\right) - 1\right]$$

5) At high reverse voltage:

$$I_R = I_S = 0.04\ \mu A$$

6) $C_D = C_{Dn} + C_{Dp}$

$L_p^2 = \tau_p D_p \longrightarrow \tau_p = L_p^2 / D_p$

$L_n^2 = \tau_n D_n \longrightarrow \tau_n = L_n^2 / D_n$

$$C_{Dp} = \tau_p \frac{I_F}{\eta V_T}$$

$$C_{Dn} = \tau_n \frac{I_F}{\eta V_T}$$